Chapter 10

Dry mix design

10.1 Overview

The objective of dry mix design is to determine the amount of various sizes of mineral aggregates to use to get a mix of maximum density. The dry mix design involves three important steps, viz. selection of aggregates, aggregates gradation, and proportion of aggregates, which are discussed below.

10.2 Selection of aggregates

The desirable qualities of a bituminous paving mixture are dependent to a considerable degree on the nature of the aggregates used. Aggregates are classified as coarse, fine, and filler. The function of the coarse aggregates in contributing to the stability of a bituminous paving mixture is largely due to interlocking and frictional resistance of adjacent particles. Similarly, fines or sand contributes to stability failure function in filling the voids between coarse aggregates. Mineral filler is largely visualized as a void filling agent. Crushed aggregates and sharp sands produce higher stability of the mix when compared with gravel and rounded sands.

10.3 Aggregate gradation

The properties of the bituminous mix including the density and stability are very much dependent on the aggregates and their grain size distribution. Gradation has a profound effect on mix performance. It might be reasonable to believe that the best gradation is one that produces maximum density. This would involve a particle arrangement where smaller particles are packed between larger particles, thus reducing the void space between particles. This create more particle-to-particle contact, which in bituminous pavements would increase stability and reduce water infiltration. However, some minimum amount of void space is necessary to:

- provide adequate volume for the binder to occupy,
- promote rapid drainage, and
- provide resistance to frost action for base and sub base courses.

A dense mixture may be obtained when this particle size distribution follows Fuller law which is expressed as:

$$p = 100 \left(\frac{d}{D} \right)^n \tag{10.1}$$

where, p is the percent by weight of the total mixture passing any given sieve sized, D is the size of the largest particle in that mixture, and n is the parameter depending on the shape of the aggregate (0.5 for perfectly rounded particles). Based on this law Fuller-Thompson gradation charts were developed by adjusting the parameter n for fineness or coarseness of aggregates. Practical considerations like construction, layer thickness, workability, etc, are also considered. For example Table 10:1 provides a typical gradation for bituminous concrete for a thickness of 40 mm.

Table 10:1: Specified gradation of aggregates for BC surface course of 40 mm

Sieve size (mm)	Wt passing (%) Grade 1	Wt passing (%) Grade 2
20	-	100
12.5	100	80-100
10.0	80 - 100	70 - 90
4.75	55 - 75	50 - 70
2.36	35 - 50	35 - 50
0.60	18 - 29	18 - 29
0.30	13 - 23	13 - 23
0.15	8 - 16	8 - 16
0.075	4 - 10	4 - 10
Binder*	5 - 7.5	5 - 7.5

Bitumen content in percent by weight of the mix

10.4 Proportioning of aggregates

After selecting the aggregates and their gradation, proportioning of aggregates has to be done and following are the common methods of proportioning of aggregates:

- **Trial and error procedure**: Vary the proportion of materials until the required aggregate gradation is achieved.
- **Graphical Methods**: Two graphical methods in common use for proportioning of aggregates are, Triangular chart method and Roch's method. The former is used when only three materials are to be mixed.
- **Analytical Method**: In this method a system of equations are developed based on the gradation of each aggregates, required gradation, and solved by numerical methods. With the advent of computer, this method is becoming popular and is discussed below. The resulting solution gives the proportion of each type of material required for the given aggregate gradation.

10.5 Example 1

The gradation required for a typical mix is given in Table 10:2 in column 1 and 2. The gradation of available for three types of aggregate A, B, and C are given in column 3, 4, and 5. Determine the proportions of A,B and C if mixed will get the required gradation in column 2.

Table 10:2: Gradation

Sieve size (mm) (1)	Required Gradation Range (2)	Filler (A) (3)	Fine Aggr. (B) (4)	Coarse Aggr. (C) (5)
25.4	100.0	100.0	100.0	100.0
12.7	90-100	100.0	100.0	94.0
4.76	60-75	100.0	100.0	54.0
1.18	40-55	100.0	66.4	31.3
0.3	20-35	100.0	26.0	22.8
0.15	12-22	73.6	17.6	9.0
0.075	5-10	40.1	5.0	3.1

Solution The solution is obtained by constructing a set of equations considering the lower and upper limits of the required gradation as well as the percentage passing of each type of aggregate. The decision need to take is the proportion of aggregate A, B, C need to be blended to get the gradation of column 2. Let x_1, x_2, x_3 represent the proportion of A, B, and C respectively. Equation of the form $ax_1 + bx_2 + cx_3 \leq p_l$ or $\geq p_v$ can be written for each sieve size, where a, b, c is the proportion of aggregates A, B, and C passing for that sieve size and p_l and p_v are the required gradation for that sieve size. This will lead to the following system of equations:

$$\begin{array}{rrrcl}
x_1+ & x_2+ & x_3 & = & 1 \\
x_1+ & x_2+ & 0.94x_3 & \geq & 0.90 \\
x_1+ & x_2+ & 0.94x_3 & \leq & 1.0 \\
x_1+ & x_2+ & 0.54x_3 & \geq & 0.6 \\
x_1+ & x_2+ & 0.54x_3 & \leq & 0.75 \\
x_1+ & 0.664x_2+ & 0.313x_3 & \geq & 0.4 \\
x_1+ & 0.664x_2+ & 0.313x_3 & \leq & 0.55 \\
x_1+ & 0.260x_2+ & 0.228x_3 & \geq & 0.2 \\
x_1+ & 0.260x_2+ & 0.228x_3 & \leq & 0.35 \\
0.736x_1+ & 0.176x_2+ & 0.09x_3 & \geq & 0.12 \\
0.736x_1+ & 0.176x_2+ & 0.09x_3 & \leq & 0.22 \\
0.401x_1+ & 0.050x_2+ & 0.031x_3 & \geq & 0.05 \\
0.401x_1+ & 0.050x_2+ & 0.031x_3 & \leq & 0.10
\end{array} \tag{10.2}$$

Solving the above system of equations manually is extremely difficult. Good computer programs are required to solve this. Software like solver in Excel and Matlab can be used. Soving this set of equations is outside the scope of this book. Suppose the solution to this problem is $x_1 = 0.05$, $x_2 = 0.3$, $x_3 = 0.65$. Then Table 10:3 shows how when these proportions of aggregates A, B, and C are combined, produces the required gradation.

10.6 Summary

Various steps involved in the dry mix design were discussed. Gradation aims at reducing the void space, thus improving the performance of the mix. Proportioning is done by trial and error and graphical methods.

10.7 Problems

1. Fullers law is expressed as
   (a) p=100$\times \left[\frac{d}{D}\right]^n$
   (b) p=100$\times \left[\frac{D}{d}\right]^n$

Table 10:3: Result of mix design

Sieve size (mm) (1)	Filler (A) (2)	Fine Aggr. (B) (3)	Coarse Aggr. (C) (4)	Combined Gradation Obtained (5)	Required Gradation Range (6)
25.4	100x0.05=5.0	100x0.3=30.0	100x.65=65	100	100
12.7	100x0.05=5.0	100x0.3=30.0	94x0.65=61	96	90-100
4.76	100x0.05=5.0	100x0.3=30.0	54x0.65=35.1	70.1	60-75
1.18	100x0.05=5.0	66.4x0.3=19.8	31.3x0.65=20.4	45.2	40-55
0.3	100x0.05=5.0	26.3x0.3=07.8	22.8x.65=14.8	27.6	20-35
0.15	73.6x0.05=3.7	17.6x0.3=05.3	9x0.65=5.9	14.9	12-22
0.75	40.1x0.05=2.0	5x0.3=01.5	3.1x0.65=2.0	5.5	5-10

(c) p=100$\times \left[\frac{d^2}{D}\right]^n$

(d) p=100$\times \left[\frac{d}{D^2}\right]^n$

Solutions

1. Fullers law is expressed as

   (a) p=100$\times \left[\frac{d}{D}\right]^n$ $\checkmark$

   (b) p=100$\times \left[\frac{D}{d}\right]^n$

   (c) p=100$\times \left[\frac{d^2}{D}\right]^n$

   (d) p=100$\times \left[\frac{d}{D^2}\right]^n$

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Chapter 11

Marshall Mix Design

11.1 Overview

OBC

The mix design (wetmix) determines the optimum bitumen content. This is preceded by the dry mix design discussed in the previous chapter. There are many methods available for mix design which vary in the size of the test specimen, compaction, and other test specifications. Marshall method of mix design is the most popular one and is discussed below.

11.2 Marshall mix design

The Marshall stability and flow test provides the performance prediction measure for the Marshall mix design method. The stability portion of the test measures the maximum load supported by the test specimen at a loading rate of 50.8 mm/minute. Load is applied to the specimen till failure, and the maximum load is designated as stability. During the loading, an attached dial gauge measures the specimen's plastic flow (deformation) due to the loading. The flow value is recorded in 0.25 mm (0.01 inch) increments at the same time when the maximum load is recorded. The important steps involved in marshal mix design are summarized next.

11.3 Specimen preparation

Approximately 1200gm of aggregates and filler is heated to a temperature of $175 - 190^oC$. Bitumen is heated to a temperature of $121 - 125^oC$ with the first trial percentage of bitumen (say 3.5 or 4% by weight of the mineral aggregates). The heated aggregates and bitumen are thoroughly mixed at a temperature of $154 - 160^oC$. The mix is placed in a preheated mould and compacted by a rammer with 50 blows on either side at temperature of 138^oC to 149^oC. The weight of mixed aggregates taken for the preparation of the specimen may be suitably altered to obtain a compacted thickness of 63.5+/-3 mm. Vary the bitumen content in the next trial by +0.5% and repeat the above procedure. Number of trials are predetermined. The prepared mould is loaded in the Marshall test setup as shown in the figure 11:1. ¡center¿ ¡param name=”movie” value=”../../0images/p21mar-test.swf”¿ ¡param name=”quality” value=”high”¿ ¡embed src=”../../0images/p21mar-test.swf” quality=”high” width=”600” height=”400”¿¡/embed¿ ¡h3¿Marshall Mould¡/h3¿ ¡/center¿

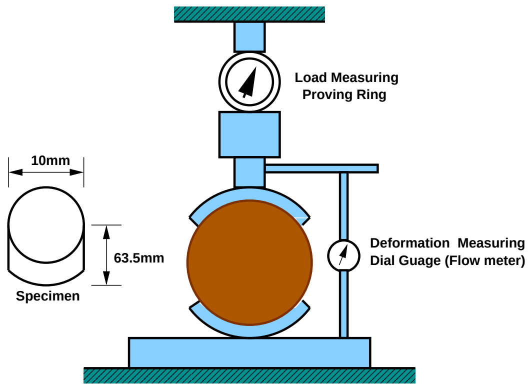

Figure 11:1: Marshall test setup

11.4 Properties of the mix

The properties that are of interest include the theoretical specific gravity G_t, the bulk specific gravity of the mix G_m, percent air voids V_v, percent volume of bitumen V_b, percent void in mixed aggregate VMA and percent voids filled with bitumen VFB. These calculations are discussed next. To understand these calculation a phase diagram is given in Figure 11:2.

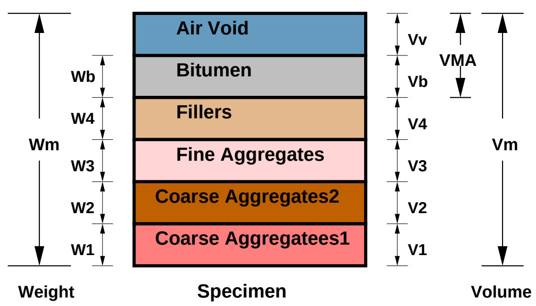

Figure 11:2: Phase diagram of a bituminous mix

11.4.1 Theoretical specific gravity of the mix G_t

Theoretical specific gravity G_t is the specific gravity without considering air voids, and is given by:

$$G_t = \frac{W_1 + W_2 + W_3 + W_b}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_b}{G_b}} \tag{11.1}$$

where, W_1 is the weight of coarse aggregate in the total mix, W_2 is the weight of fine aggregate in the total mix, W_3 is the weight of filler in the total mix, W_b is the weight of bitumen in the total mix, G_1 is the apparent specific gravity of coarse aggregate, G_2 is the apparent specific gravity of fine aggregate, G_3 is the apparent specific gravity of filler and G_b is the apparent specific gravity of bitumen,

11.4.2 Bulk specific gravity of mix G_m

The bulk specific gravity or the actual specific gravity of the mix G_m is the specific gravity considering air voids and is found out by:

$$G_m = \frac{W_m}{W_m - W_w} \tag{11.2}$$

where, W_m is the weight of mix in air, W_w is the weight of mix in water, Note that $W_m - W_w$ gives the volume of the mix. Sometimes to get accurate bulk specific gravity, the specimen is coated with thin film of paraffin wax, when weight is taken in the water. This, however requires to consider the weight and volume of wax in the calculations.

11.4.3 Air voids percent V_v

Air voids V_v is the percent of air voids by volume in the specimen and is given by:

$$V_v = \frac{(G_t - G_m)100}{G_t} \tag{11.3}$$

where G_t is the theoretical specific gravity of the mix, given by equation 26.1. and G_m is the bulk or actual specific gravity of the mix given by equation 26.2.

11.4.4 Percent volume of bitumen V_b

The volume of bitumen V_b is the percent of volume of bitumen to the total volume and given by:

$$V_b = \frac{\frac{W_b}{G_b}}{\frac{W_1+W_2+W_3+W_b}{G_m}} \tag{11.4}$$

where, W_1 is the weight of coarse aggregate in the total mix, W_2 is the weight of fine aggregate in the total mix, W_3 is the weight of filler in the total mix, W_b is the weight of bitumen in the total mix, G_b is the apparent specific gravity of bitumen, and G_m is the bulk specific gravity of mix given by equation 26.2.

11.4.5 Voids in mineral aggregateVMA

Voids in mineral aggregate VMA is the volume of voids in the aggregates, and is the sum of air voids and volume of bitumen, and is calculated from

$$VMA = V_v + V_b \tag{11.5}$$

where, V_v is the percent air voids in the mix, given by equation 26.3. and V_b is percent bitumen content in the mix, given by equation 26.4. (11.4).

11.4.6 Voids filled with bitumen VFB

Voids filled with bitumen VFB is the voids in the mineral aggregate frame work filled with the bitumen, and is calculated as:

$$VFB = \frac{V_b \times 100}{VMA} \tag{11.6}$$

where, V_b is percent bitumen content in the mix, given by equation 26.4. and VMA is the percent voids in the mineral aggregate, given by equation 26.5.

11.5 Determine Marshall stability and flow

Marshall stability of a test specimen is the maximum load required to produce failure when the specimen is preheated to a prescribed temperature placed in a special test head and the load is applied at a constant strain (5 cm per minute). While the stability test is in progress dial gauge is used to measure the vertical deformation of the specimen. The deformation at the failure point expressed in units of 0.25 mm is called the Marshall flow value of the specimen.

11.6 Apply stability correction

It is possible while making the specimen the thickness slightly vary from the standard specification of 63.5 mm. Therefore, measured stability values need to be corrected to those which would have been obtained if the specimens had been exactly 63.5 mm. This is done by multiplying each measured stability value by an appropriated correlation factors as given in Table below.

Table 11:1: Correction factors for Marshall stability values

Volume of specimen (cm^3)	Thickness of specimen (mm)	Correction Factor
457 - 470	57.1	1.19
471 - 482	68.7	1.14
483 - 495	60.3	1.09
496 - 508	61.9	1.04
509 - 522	63.5	1.00
523 - 535	65.1	0.96
536 - 546	66.7	0.93
547 - 559	68.3	0.89
560 - 573	69.9	0.86

11.7 Prepare graphical plots

The average value of the above properties are determined for each mix with different bitumen content and the following graphical plots are prepared:

1. Binder content versus corrected Marshall stability
2. Binder content versus Marshall flow
3. Binder content versus percentage of void (V_v) in the total mix
4. Binder content versus voids filled with bitumen (VFB)
5. Binder content versus unit weight or bulk specific gravity (G_m)

11.8 Determine optimum bitumen content

Determine the optimum binder content for the mix design by taking average value of the following three bitumen contents found form the graphs obtained in the previous step.

1. Binder content corresponding to maximum stability

2. Binder content corresponding to maximum bulk specific gravity (G_m)

3. Binder content corresponding to the median of designed limits of percent air voids (V_v) in the total mix (i.e. 4%)

The stability value, flow value, and VFB are checked with Marshall mix design specification chart given in Table below. Mixes with very high stability value and low flow value are not desirable as the pavements constructed with such mixes are likely to develop cracks due to heavy moving loads. ¡center¿ ¡param name="movie" value="../../0images/p22mar-charts.swf"¿

Table 11:2: Marshall mix design specification

Test Property	Specified Value
Marshall stability, kg	340 (minimum)
Flow value, 0.25 mm units	8 - 17
Percent air voids in the mix V_v%	3 - 5
Voids filled with bitumen VFB%	75 - 85

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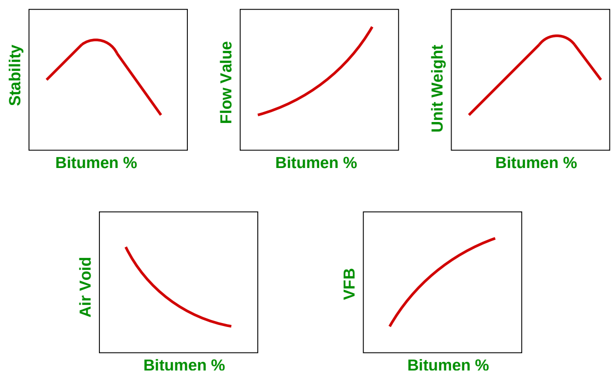

Figure 11:3: Marshal graphical plots

11.9 Numerical example - 1

The specific gravities and weight proportions for aggregate and bitumen are as under for the preparation of Marshall mix design. The volume and weight of one Marshall specimen was found to be 475 cc and 1100 gm. Assuming absorption of bitumen in aggregate is zero, find V_v, V_b, VMA and VFB;

Item	A_1	A_2	A_3	A_4	B
Wt (gm)	825	1200	325	150	100
Sp. Gr	2.63	2.51	2.46	2.43	1.05

Solution

$$\begin{aligned}
G_t &= \frac{825+1200+325+150+100}{\frac{825}{2.63}+\frac{1200}{2.51}+\frac{325}{2.46}+\frac{150}{2.43}+\frac{100}{1.05}} \\
&= \frac{2600}{1080.86} \\
&= 2.406 \\
G_m &= \frac{1100}{475} \\
&= 2.316 \\
V_v &= \frac{2.406-2.316}{2.406} \times 100 \\
&= 3.741\ \% \\
V_b &= \frac{100}{1.05} \times \frac{2.316}{1100} \\
&= 20.052\ \% \\
VMA &= (3.741+20.05) \\
&= 23.793\ \% \\
VFB &= \frac{20.052}{23.793} \times 100 \\
&= 84.277\ \%
\end{aligned}$$

11.10 Numerical example - 2

The results of Marshall test for five specimen is given below. Find the optimum bitumen content of the mix.

Solution Plot the graphs and find bitumen content corresponding to

1. Max stability = 5 percent bitumen content.

Bitumen content	Stability (kg)	Flow (units)	V_v (%)	VFB (%)	G_m
3	499.4	9.0	12.5	34	2.17
4	717.3	9.6	7.2	65	2.21
5	812.7	12.0	3.9	84	2.26
6	767.3	14.8	2.4	91	2.23
7	662.8	19.5	1.9	93	2.18

2. Max G_m = 5 percent bitumen content.
3. 4% percent air void = 3 percent bitumen content.

The optimum bitumen extent is the average of above = 4.33 percent.

11.11 Summary

Marshal stability test is the performance prediction measure conducted on the bituminous nix. The procedure consists of determination of properties of mix, Marshal stability and flow analysis and finally determination of optimum bitumen content. The concept of phase diagram is used for the calculations.

11.12 Problems

1. In Marshall stability test, the sample is compacted using a rammer giving
   (a) 50 blows
   (b) 20 blows
   (c) 25 blows
   (d) 75 blows
2. The Marshall flow value is expressed in units of
   (a) 25 mm
   (b) 2.5mm
   (c) 5mm
   (d) 3mm

11.13 Solutions

1. In Marshall stability test, the sample is compacted using a rammer giving
   (a) 50 blows√
   (b) 20 blows
   (c) 25 blows
   (d) 75 blows
2. The Marshall flow value is expressed in units of
   (a) 25 mm
   (b) 2.5mm√
   (c) 5mm
   (d) 3mm